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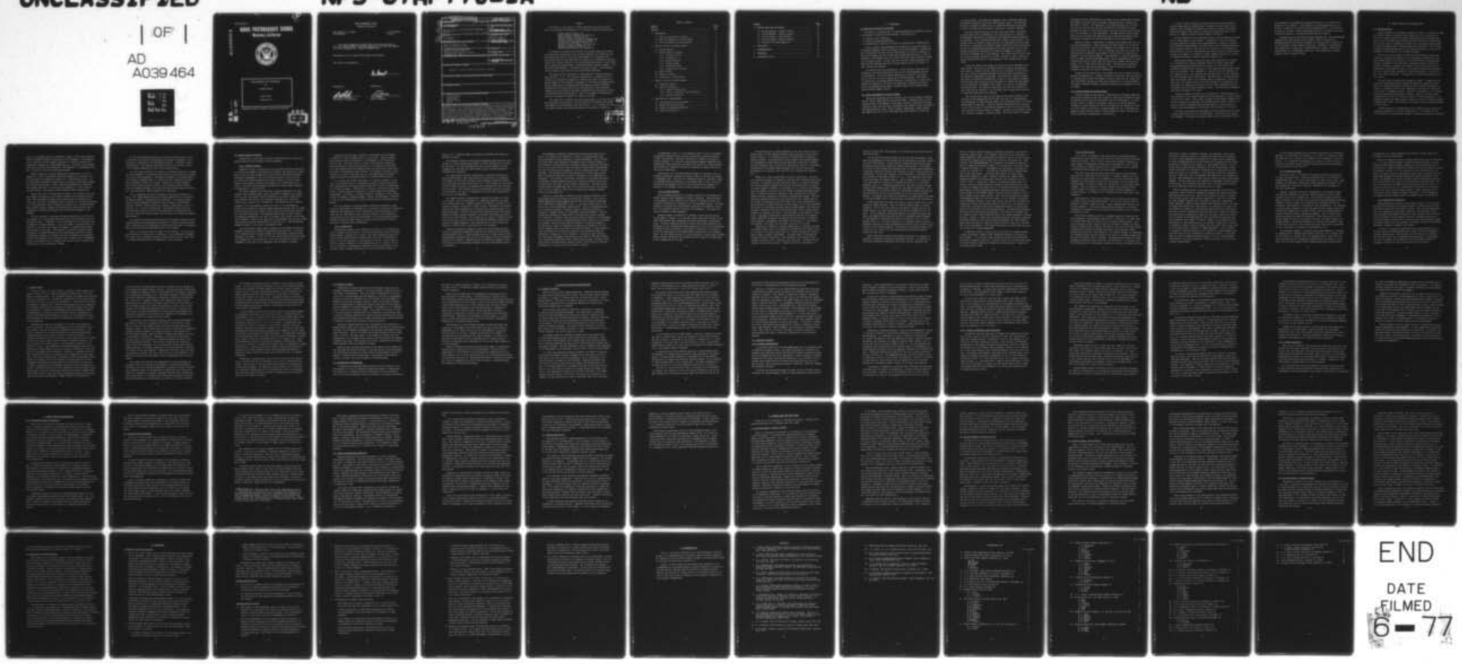

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

DECISION-MAKING AND OPTIMIZATION

IN

AIRCRAFT DESIGN

Ulrich Haupt

February 1977

Approved for public release; Distribution unlimited

NAVAL POSTGRADUATE SCHOOL

Monterey, California

Rear Admiral I. W. Linder
Superintendent

J. R. Borsting
Provost

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The state of the art in aircraft design is surveyed with regard to the decision-making process. It is shown that the empirical approach to decision-making as it is generally practiced in hardware design has inherent limitations. There is an increasing need to consider uncertainties and preferences explicitly. This leads to a new design outlook combining the experience of old-time designers with an analytical approach to complex problems. An outline is given for the development of practice-oriented text material as a most essential step toward preparing engineers for new tasks in design and decision-making.

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PREFACE

This report is the outcome of visits which were made during the past year to the engineering departments of the following aircraft manufacturers:

Boeing Company, Seattle, WA,
Douglas Aircraft Company, Long Beach, CA
General Dynamics, Fort Worth, TX,
Grumann Aerospace Corporation, Bethpage, NY,
Lockheed Aircraft Corporation, Burbank, CA,
LTV Aerospace Corporation, Dallas, TX,
McDonnell Aircraft Company, St. Louis, MO,
Northrop Corporation, Hawthorne, CA,
Rockwell International, Los Angeles, CA.

The visits were sponsored by the Naval Air Systems Command and, thanks to the excellent cooperation of the aircraft companies, the opportunity was provided at each place to talk with a good number of those engineers who have accumulated the broad experience so essential as a background for design. Others with a personal interest in the decision-making process, at universities and in engineering organizations, provided additional valuable comments. All those who were contacted -- too many to be listed by name -- gave generously of their precious time and their rich professional experience.

The author has been interested in basic aspects of aircraft design for some time (Ref. 1 & 2). His views are conditioned by a background of two decades as an aeronautical engineer in industry and almost two decades as a faculty member in the Aeronautics Department of the Naval Postgraduate School and are tempered by the somewhat detached attitude of being an emeritus. Nevertheless, conclusions drawn from a wide spectrum of well-considered comments and reflections are unavoidably simplified and influenced by subjective observation and interpretation. They are the author's responsibility and do not necessarily represent the policy of the NASC.

The reader who is familiar with recent developments in aircraft design may conveniently skip Section 2, and the reader who is familiar with recent developments in decision-making may skip Section 3. Or, if pressed for time very badly, one may just peruse and ponder the conclusions of Section 6.

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1. INTRODUCTION

1.1 Objective and Method of Approach

This report is concerned with the decision-making and optimization process in the design of advanced aircraft systems. The objective is

. to evaluate recent experience;

. to clarify existing problem areas;

. to establish basic needs and to arrive at conclusions and recommendations.

At first glance, decision-making and optimization in aircraft design has a different appearance from the viewpoint of the vice-president of engineering who is responsible for basic policy considerations, or from the viewpoint of the project engineer who has to make major engineering decisions, or from the viewpoint of the designer who has to make all the many daily decisions throughout the design process. A closer look will provide a common denominator for these various viewpoints and show the basic significance of the subject to every aeronautical engineer.

To establish the proper perspective, a brief outline of some basic developments in aircraft design and of the role of decision-making serves as an introduction. The two following chapters give a review of the present state of the art in aircraft design and in decision-making. This leads to a clarification of existing problem areas and a consideration of basic needs. Finally the findings of the report are summarized, conclusions are drawn, and two recommendations are made to initiate modest "seed" programs which should provide tangible results.

1.2 Basic Developments in Aircraft Design

During the pioneering years of aviation, the aircraft designer frequently was the central figure and the jack-of-all-trades -- designer as well as main resource person in aerodynamics, structures, materials, propulsion, and manufacturing, often also test pilot, entrepreneur and founder of great enterprises. The Wright Brothers, Glen L. Martin, Breguet, DeHavilland, Fokker, Heinkel and Sikorsky are just a few of the names which come readily to one's mind.

A creative spirit, clear grasp of essentials, and a confidence-inspiring, self-assured personality were their characteristic traits. The knowledge necessary to design an airplane was of a practical kind and for many years it was no more than could be stored in the mind of a capable individual.

This first period had come to an end in the early 1930s. Evaluation of wind tunnel tests in aerodynamics, thin plate analysis in structures, thermodynamic efficiencies in propulsion, processing and forming techniques in production -- each of them developed into a field of specialization. The designer could not possibly keep up with all the developments and had enough difficulty to coordinate the different inputs coming from various specialists. Yet the solid engineering background and the long experience of the typical designer provided the know-how and the balanced judgment to translate new theoretical knowledge into flying hardware. This period lasted from the years of exciting technical progress in the 1930s, through the years of mass production during World War II, to the expansion of air transportation in the 1950s.

In the late 1950s a slow change in attitude took place throughout aircraft design. Partly due to the impetus given by missiles and spacecraft which began to outshine aircraft, partly due to the demands of the military who were striving for maximum performance, the importance and prestige of the analytical specialists soared high. Specialists were needed to expand the limits of scientific knowledge and to reach for ever higher performance. The best minds were attracted by the challenges of research and development which usually meant estrangement from design. As a result, the designer's prestige declined. The analytical specialist was often the originator of novel ideas and the designer, in all too many cases, played second fiddle as he translated these ideas into practice.

Then, around 1970, began the big slump in the aircraft industry with a reduction of the engineering force by about 25% (Ref. 3). Simultaneously, two developments of great potential impact and far-reaching effect on aircraft design began to take place. Firstly, computer-aided design came of age and is now in the process of relieving the designer of much of the earlier drudgery regarding the menial aspects of design. Secondly, the procurement policy of the military underwent a thorough change: The earlier drive for maximum

performance has been superseded by a new quest for an optimal balance between performance, life-cycle cost, reliability, maintainability, vulnerability, and other "-ilities". The experience of the 1960s had shown that for military aircraft the price for the last few ounces of performance is usually excessive in terms of other characteristics and that the total overall system has to be optimized, not just performance. The same lesson had been learned earlier by the airlines where meticulous cost accounting had pointed toward the possible savings due to improved reliability and maintainability.

These two trends -- rapid growth of computer-aided design (CAD) and need for system optimization -- have developed into major aspects of aircraft design in the mid-1970s. Both put new demands on the designer but at the same time they provide new vistas. CAD is a promising tool which can replace the drafting board (a negative status symbol) by the screen with light pen and keyboard (a positive status symbol). More important, it frees the designer's mind for higher and more challenging tasks. Such a challenging task is system optimization which has always been the ultimate but somewhat remote goal of design. Now it comes within practical reach. CAD and system optimization complement each other because CAD makes it easy to explore new ideas and alternative solutions for overall optimization.

Viewed from this perspective, the designer will have to assume new and broader responsibilities. Actually, they are not quite new. They are the kind of responsibilities which the designer carried in times when the design position held highest prestige and which were discarded more or less by default. The present situation provides a promising opportunity to reappraise the role of design.

1.3 Aircraft Design and Decision-making

Aircraft design has many aspects. Unfortunately, the general image has been distorted during the past two decades by picturing the designer as mostly concerned with nuts and bolts and slaving over the drawing board. It should be more correct to think of the designer firstly as a creative engineer; secondly as a master planner who has to anticipate how the design will stand up in the future; and thirdly as a design manager who has to understand the essence of many different fields of specialization in order to balance the often conflicting recommendations of specialists.

In terms of mental disciplines, design requires some basic qualities: creative imagination and inventiveness to produce alternative ideas and to visualize their consequences; analytical thinking to provide the necessary depth of perception; and a sense of synthesis to develop the width of perspective for making a prudent decision between alternatives.

The much neglected but very pervasive aspect of decision-making in design forms the main subject of this report. To appreciate it one must realize the basic difference between science and engineering. Science is concerned with fundamental understanding. It starts with a clearly defined problem and if the original problem is too difficult for solution, it is simplified or subdivided until it can be analyzed and the correct solution is found. During the past two decades, in a climate of rapidly expanding frontiers of science, the analytical methods of science played the dominant role.

Engineering, however, is much more than a mere application of science. It is concerned with creating technical products to fulfill human needs. The engineering process begins with the concept of a goal which may be achieved in different ways. The goal is often poorly defined and takes firmer shape only gradually. Each component of a solution has to be analyzed, but all components have to be integrated and decisions have to be made regarding the choice between various alternatives. The main burden of decision-making falls upon design, which is the planning stage of engineering. Design decisions have to be made not only by the chief designer who is responsible for all aspects of a design but just as well by the detail designer who may be responsible only for a small attachment bracket. Decision-making accompanies the designer throughout his career.

These few remarks may suffice as an introduction. Their purpose is to focus attention on the unique situation which has developed in aircraft design in the past few years. CAD provides the means for man-computer communication in real time and for optimizing a well defined design concept. However, it does not relieve the designer from decision-making. On the contrary, it brings out decision-making as the principal task of design at all levels.

For about two decades the significance of decision-making and the corresponding implications have been overshadowed by a preoccupation with analytical methods. A different trend began tenderly in the early 1960s and was

well documented in the Educational Development Project of the University of California at Los Angeles. A new emphasis in engineering education was to be given to design as an iterative decision-making activity. Yet this idea was ahead of its time. Neither engineering education nor industry were ready to give much thought to the decision-making process in design.

It appears that the time should be more favorable now. Much has happened throughout the world during the past decade to make us realize that a deterministic-analytical mind is necessary for the perfection of details but is not sufficient to make important decisions. Awareness of uncertainties and integration of details into a larger system are needed. Both analysis and synthesis have to complement each other. Decision-making in aircraft design is just one aspect of this.

2. STATE OF THE ART IN AIRCRAFT DESIGN

2.1 Design Hierarchy

Design consists of a hierarchical sequence of steps. It begins with ideas and concepts; takes successively firmer shape until the configuration can be frozen; continues with the practical considerations about hardware; and leads to a set of manufacturing instructions and airworthiness documentation. We will steer clear of labeling the various levels and phases because enough overlap and confusion exist already in names and definitions. Yet it should be useful to summarize what goes into the design process and to show how the designer's outlook changes as the design progresses.

The initial step of design is concerned with formulating concept and objective; studying the feasibility of an approximate configuration; examining proposed mission and operation of the final product; clarifying needs, criteria, assumptions, and constraints; appraising available resources of know-how, man-power, equipment, and funding; evaluating uncertainties and competition; establishing priorities; and estimating impact and consequences. All this is based on much experience, a realistic appraisal of given facts, and a few rough calculations. The decisions are directed toward go/no go of the project.

The next step is concerned with parametric sizing. It begins with the analytical relationships between design and performance parameters, which have to be refined eventually by windtunnel data to support performance estimates. Alternative solutions are compared and trade-offs are carried out on the level of parametric studies. Variation of parameters is an iterative analytical process directed toward synthesis - namely to find an optimal configuration which can be frozen with respect to overall dimensions. Such parametric studies are based on laws of physics as well as on experience which considers many aspects. The decisions are directed toward an optimal geometry of the aircraft.

Hardware design is a continuation of this formative process. Within the constraints imposed by the chosen configuration it is concerned with the actual hardware of structures and systems. Alternative solutions and tradeoffs

have to be considered just as in parametric studies -- but now the practical level of hardware replaces the abstract level of parameters. Each component part is analyzed from the separate viewpoints of function, strength, cost, reliability, producibility, maintainability, etc. Structural and functional tests may be required for verification. The emphasis is on engineering know-how. Decisions are directed toward manufacturing.

Finally design has to supply manufacturing instructions in form of a drawing or a tape for numerically controlled production. In addition, airworthiness must be documented by analysis or demonstrated by tests. All the information developed previously must be followed up thoroughly, integrated, verified and recorded. Close liaison with manufacturing, inspection, and customer acceptance is required and the emphasis is on full attention to final details. Decisions are directed mainly toward clarification.

Beyond this there is another phase of design. It is usually called product support and pertains to the liaison between service experience and design. Some maintenance problems always develop after the introduction of a new type of aircraft and designers have to take part in the trouble-shooting. Or, on the other hand, when an aircraft has matured into a successful model, there usually develops a demand for modifications, growth versions, and incorporation of advanced technologies which pose many challenges for the designer.

All this indicates a consistent continuity reaching from the first design concept to the last design modification which may take place more than two decades later. In addition to this chronological set of activities, one can speak of a design hierarchy -- not in the sense of an authoritative process but in the sense of an orderly arrangement of responsibilities which are different at each level. For instance, in the early conceptual phases of design it is established whether the wing-fuselage intersection should be high-wing, mid-wing, or low-wing; wing area and geometry are determined later on the parametric level of design; spar, stringer, and rib arrangement early on the hardware level of design; bolt and rivet sizes or material processing only in the final phases of design.

At any level previous decisions have become constraints and no new decisions must be made without anticipating all possible consequences. This continuity is expressed in the term design hierarchy. It implies a double responsibility -- for analysis appropriate to the level of design as well as for synthesis regarding the entity of the design process.

The term design hierarchy also implies two different viewpoints in design. The system designer is concerned primarily with the end product which consists, of course, of many components. The component designer is concerned primarily with a specific component which, of course, has to be integrated with many other components to result in a system. Therefore, the system designer starts from an abstract goal to arrive at the necessary physical aspects while the component designer starts from practical physical aspects to arrive at a final end product. Design comprises both viewpoints.

The two viewpoints have been accentuated by two different kinds of experts. For systems design there is the systems engineer who is an expert on the general aspects of integrating many components. For component design there are many technological specialists who are experts on performance, stability, fatigue, fracture mechanics, corrosion, producibility, cost, reliability, etc. As the old saying goes: the generalist learns less and less about more and more until he knows nothing about everything while the specialist learns more and more about less and less until he knows everything about nothing.

For about two decades the designer has been increasingly squeezed between systems engineers and technological specialists. If systems engineers provide width of perspective and technological specialists provide depth of perception, what are the functions and responsibilities of the designer?

There is no unanimity about an answer to this question. Yet the differences refer more to nuances than to substance. The considerations throughout this report about the present situation, problem areas, and basic needs lead to a design outlook which will be summarized in the conclusions.

2.2 Typical Aspects of Design

Consideration of some typical aspects of design may help to clarify the design process from the viewpoint of decision-making.

2.2.1 Parametric Sizing

Parametric sizing is concerned with the trade-offs which are characteristic of the early phases in the design of an aircraft. The purpose is to determine the best aircraft configuration which satisfies specified performance and mission requirements. This is an iterative process of trial and error by varying some chosen parameters while other variables are held constant. Among the many possible solutions the designer has to decide which one to choose. Vice versa, the performance resulting from chosen design parameters is determined as a closed solution.

The various parameters can be grouped as design parameters (e.g. wing loading, thrust loading, aspect ratio), performance parameters (e.g. speed, rate of climb, turn radius), mission parameters (e.g. range, flight trajectory, maneuver load factor), and technology parameters (e.g. structural weight, C_L/C_D , specific fuel consumption). The number and type of design parameters to be used depend on purpose and level of the investigation. During the early phases of advanced design unnecessary details must be avoided not only because they cost computer time but also because they mean undesirable constraints downstream. For subsequent phases which are more refined, the geometric parameters of the wing, for instance, may include not only wing area, sweepback, aspect ratio, taper ratio, and thickness ratio but also airfoil characteristics and size and deflection of flap and slat. Final performance parameters depend on the results of windtunnel tests.

The relationships between design parameters and performance and mission parameters become quite complex for high-performance aircraft. It is feasible to establish them in separate modules for aerodynamics, propulsion, mass properties, structures, or cost, so that they can be updated and refined under the jurisdiction of each discipline. Yet at the same time the modules are integrated so that data can be transferred from one module to another.

Computerization has made it possible to investigate the large number of parameters at various combinations in a short time. Computer programs have been used either in batch mode or, increasingly, in the interactive graphics mode. The latter offers, of course, the important advantage of rapid man-computer interaction with display on the cathode-ray tube (CRT). As an idea flashes across the designer's mind, the CRT provides quantitative data about its implications within seconds. The designer can modify initial questions by a touch of the light pen or of the alpha-numerical keyboard -- a gradual evolution from parametric analysis to design-oriented analysis.

For an innovative design, development of a computer program is a major task. On the other hand, for a conventional design the basic equations are well established and the program usually begins with a baseline configuration for airframe and engine. Modifications are made by scaling the design parameters of various components separately to satisfy mission and performance requirements. The output of a typical program for parametric sizing consists of data for geometry, component weights, balance, and performance. Additional data on cost and structures can also be obtained from corresponding input modules.

From the viewpoint of decision-making, computerized parametric sizing provides a large amount of information in a form which can easily be interpreted. Trade-offs and sensitivities can be assessed and the decision-maker is provided with the information to make a rational decision. Yet availability of information is only one of the ingredients of the decision-making process. Parametric sizing by itself remains an analytical trial-and-error process and gives no assurance about optimization.

2.2.2 Optimization

Optimization requires a clear definition of what is to be optimized and this is frequently quite elusive. A clear-cut problem may consist of finding minimum weight or maximum rate of climb. More often optimization means the proper balance between several characteristics which may be ill-defined or subject to various influences or vacillations of opinion. In such cases an objective function depends on a multi-dimensioned set of criteria. The objective function is a mathematical expression of the decision-maker's value system in terms of design parameters and it will be discussed further in

Section 3.2.1. Different types of aircraft are optimized with respect to different criteria.

For transport aircraft with specified performance characteristics, optimization is usually required with respect to direct operating cost in cents per seat mile. Yet other considerations such as noise footprint or fuel consumption per seat mile may easily assume a major role when supersonic transports are considered.

For some military aircraft, optimization is required with respect to mission effectiveness. Many other military aircraft have to be optimized with respect to life-cycle cost which, under peacetime conditions, amounts to several times the initial acquisition cost. This includes cost of development and production as well as operation and maintenance over the life span of the aircraft. Until recently the military services were mostly concerned with acquisition cost and as a consequence statistical data on operational cost are not very plentiful.

For fighter aircraft, optimization is required with respect to "wins" in air combat. This is established by an additional simulator loop which can be incorporated into a computer program. The simulator consists of the aircraft's cockpit, equipped with flight controls, instruments, and interconnected visual display systems and a correspondingly equipped cockpit of an adversary aircraft. The pilot in each cockpit operates in real time through digital and analog computer equipment in accordance with design and performance data of each aircraft. Each cockpit may be movable to produce acceleration on the pilot, and all data are recorded for subsequent analysis as a function of design parameters. Both characteristics of the aircraft and actions of the pilot form a unity which has to be optimized.

Beyond the problems of defining criteria for the objective function, there are considerable mathematical difficulties connected with the optimization procedure itself. Design problems often have so many variables with interdependent constraints that the use of differential calculus or graphical methods is not feasible. Employing numerical optimization methods is more practical and has the additional advantage that they lend themselves easily to automation.

Much progress in numerical optimization has been made during the last decade. Any design can be defined by a vector in multidimensional space where each design variable represents a different dimension. Since we cannot see in more than three dimensions, the general case is beyond our power of visualization. Yet the principle is the same as when we assume only two variables in a base plane and plot above this plane a curved surface representing the objective function which depends on the two variables and which is to be optimized. The objective function may express cost, weight, range, aerodynamic or propulsive efficiency, return on investment, or any combination of parameters. It is subject to functional constraints in accordance with given relationships between parameters and also to regional constraints which may be specified for the upper or lower bounds of parameters. The regional constraints define the permissible part of the curved surface where the optimum value has to be found, e.g. limits due to minimum sheet thickness, maximum stress, stalling speed, etc.

There are a good number of numerical search programs available to find the optimum value on the surface of the objective function. One of them is CONMIN (Constrained Function Minimization) which was developed by NASA Ames and is described by Vanderplaats in Ref. 4. The search begins from an initial point in the n-dimensional "design space". From the corresponding point on the objective function it follows a method of feasible directions. A direction of steepest descent is calculated by finite differences. This determines the direction of search which is followed until either a minimum or a constraint is reached. When the search direction leads to a local minimum of the objective function, a modified steepest descent direction is calculated and followed. When the search direction leads to a constraint boundary, a new direction of search is determined by bisecting the tangents to the constraint boundary and to the contour of constant objective. In most practical cases the minimum of the objective function in the permissible region is approached or reached in 5 to 10 iterations. The computer logic includes, of course, many refinements which are beyond the scope of this brief outline. This optimization takes place within a given design concept. The final choice among various optimized design concepts offers no difficulties as they will be measured on the same scale and can easily be ranked.

As emphasized in Ref. 4, a very essential aspect of such an automated optimization program is that it can be coupled with an analysis program. To make this possible, a few basic rules must be observed in writing the analysis program -- for instance, using standard language; segmenting each program into input, execution, and output; and storing in a single identifiable location all parameters that may be objectives or design variables or that may be constrained.

Modification of an existing analysis program for coupling it with an automated optimization program can usually be done in less than one man-day of programming time. With the truly tremendous numbers of analytical computer programs which are available, it now becomes easy to take a step which has been quite formidable up to now: from the specialist's emphasis on analysis to the designer's outlook toward synthesis and optimization.

2.2.3 Design Synthesis

The term design synthesis is now usually applied to the automated systematic approach toward designing a system or subsystem. Design synthesis on the parametric level combines the procedures of parametric sizing with automated optimization as described in the two preceding sections. The input consists of the analytical relationships established for parametric sizing and of the objective function in terms of the parameters. The output consists of optimized design parameters.

Design synthesis is applicable to problems of many kinds and during various phases of design. Up to now most efforts have been directed to the early design phases where parameters are readily expressed in quantitative terms. A clearly formulated objective function and accurate analytical expressions for the relationships between parameters are the basic requirements. The answer cannot be expected to be creative or innovative -- obviously it is only an optimization of the design concept incorporated in the computer input. Yet with design synthesis it becomes feasible to explore many different design concepts and evaluate the optimum solution of each on an equal basis before a design decision is made.

An excellent survey of design synthesis in the early 1970s is given by Straub in Ref. 5 which summarizes various design synthesis projects undertaken by industry. To illustrate what can be accomplished in parametric design at present, in the mid-1970s, we may consider a particularly general and comprehensive program which has been developed at NASA Ames as ACSYNT (Aircraft Synthesis) and is described by Vanderplaats in Ref. 6. The modules incorporated in the ACSYNT program represent more than 100 man-years of development over a period of more than 10 years as mentioned by Gregory in Ref. 7.

ACSYNT has a control module which consists of three parts. The first part performs convergence to identify an aircraft which satisfies given specifications. The designer estimates the gross weight of a baseline configuration and the computer compares this with the sum of empirically calculated structural weights in addition to the weights of fuel, payload, and equipment. Since the weights of structure and fuel depend on design and mission parameters, an iterative process is necessary to make estimated and calculated weights the same, resulting in an initial converged gross weight. This will define the objective function but will generally not be a minimum and may not satisfy constraints such as field length, fuel volume requirements, etc. The second part of ACSYNT optimizes the gross weight (or any other parameter) and carries out the sizing function using the CONMIN program. The third part performs a sensitivity function which automatically varies a single design parameter to determine the effect of this parameter on the design of the aircraft. Convergence, optimization, and sensitivity modules are integrated within ACSYNT and incorporate the separate discipline modules in geometry, mass properties, aerodynamics, propulsion, and structures. A cost module can be added. The output data are either in print or on the CRT.

Application of ACSYNT to a typical design study of a military aircraft for a given mission profile is discussed by Vanderplaats and Gregory in Ref. 8. The goal of this early design study is to define configuration concepts and to identify research requirements. The gross weight is minimized by finding the proper combination of five parameters: wing loading, thrust loading, wing aspect ratio, thickness ratio, and sweep. Fuselage size and fineness ratio are kept constant. Using only these five parameters, an

accuracy of about 10% in gross weight can be expected from correlations with existing aircraft.

For the specified mission profile and the five chosen parameters convergence and optimization of gross weight were accomplished in less than 4 minutes on the CDC 7600 computer. Various mission definitions would obviously mean different optimized gross weights and design configurations. To determine the effects on gross weight and performance due to changing design parameters, a good many sensitivity analyses were conducted and many of them required re-optimization. Of particular interest is the sensitivity to technology factors, e.g. reduction in structural weight or in C_D. This indicates fields where research promises the highest benefits. Ref. 8 mentions 20 to 30 hours on a CDC 7600 computer as typical for a sensitivity study to 5 to 10 mission parameters and 3 to 5 technology parameters for each basic aircraft concept. Computer time increases about linearly with the number of parameters. Also the complexity of the mission profile has considerable influence because this may easily become the most time-consuming item in the various discipline modules. The computer time should be distributed over approximately two weeks to give the designer time for interpretation and discussion with specialists.

ACSYNT exemplifies how deeply and quickly a design concept can be investigated by design synthesis. There is, however, another aspect to design synthesis. This is the concern with the continuity of design from the conceptual phase to the final detail phase and with the integration of all aspects. For an integrated, interactive approach to analysis and design functions, the Computer Aided Technology Project at McDonnell Aircraft Company is representative as described by La Favor and Doelling in Ref. 9 and by English in Ref. 10. The basic principle is to coordinate computer routines developed separately in various engineering disciplines and to provide a rapid transfer of data between programs. The project is open-ended and many parts still have to be filled in but the already existing interactive graphic modules are impressive:

ICADE (Interactive Computer Aided Design Evaluation) is a program for parametric configuration sizing and performance analysis. It determines if the flight performance requirements and vehicle size are compatible and

serves to evaluate specific design or performance trade-offs, starting from a baseline design concept. CALL (Computer Aided Loft Lines) establishes a common mathematical data base defining the external shape of the aircraft and providing the designer with the mold line contour at any desired cut. CADD (Computer Aided Design/Drafting) is a program for the geometry-oriented aspects of computerized graphical design. It is used first in the early stages of design, providing routines for geometric and aerodynamic wing design on the CRT, for internal fuel volumes and their centroid within complex shapes, and for many other design applications which utilize the unique three-dimensional capability of CADD. Computer routines solve complex spatial kinematics problems like landing gear retraction and clearances or pilot's field of vision. A second use of CADD is in production design where, for instance, the flat pattern dimensions required by manufacturing can be laid out both for flanged sheet metal parts or for laminated composite structures. CGSA (Computer Graphics Structural Analysis) creates and processes finite element models so that NASTRAN (NASA's Structural Analysis program) can perform a minimum strain energy solution. Then, after the designer has created the mathematical model of a part and stored it in the computer, the manufacturing programmer retrieves a copy, adds tooling lugs and other manufacturing requirements and uses GNC (Graphics Numerical Control) for the generation of a numerically controlled (N/C) source program which defines the sculpturing process to be executed by the N/C milling machine. The manufacturing programmer depicts the cutter motions graphically on the CRT and is concerned only with geometry labels without being involved in the complex mathematics defining the part. Finally, to assure that the manufactured part accurately represents the design definition, the quality assurance programmer uses CAQA (Computer Aided Quality Assurance) to generate inspection data by light pen on the CRT. They can be transmitted to a N/C inspection machine with glass probe and print-out of actual vs. required dimensions.

A large-scale project to explore the full potential of design synthesis is under development at NASA as IPAD (Integrated Programs for Aerospace vehicle Design). It is directed toward collecting and developing operational modules and integrating them into a flexible, versatile, and open-ended system to provide automated continuity throughout the design process. Results are not expected before 1980.

2.2.4 Systems Design

On the level of parametric sizing quantitative relationships between parameters have been developed as the result of continuous efforts which have lasted over decades. When it comes to the physical aspects of hardware design, however, we depend much on qualitative considerations. For a survey of the problems of hardware design it will be convenient to make a distinction between systems design and structures design.

The terms system and sub-system are relative and not easily defined. Any system is a sub-system of the universe. A transport airplane is a sub-system for an airline which has to integrate it with other sub-systems like passenger and cargo handling, operations, maintenance, and route structure. Correspondingly, a military airplane is a sub-system of a vast defense establishment. From our viewpoint of aircraft design, the propulsion system, control system, fuel system, or avionics system are typical examples of aircraft systems. The emphasis is on a functional entity consisting of many components.

Each system has to deal with a different set of problems and requires a different kind of specialized knowledge. Yet the basic approach from the designer's viewpoint remains the same -- again combining detail analysis and overall synthesis. A functional system diagram describes how the various components are integrated into the system but any component can be a complex sub-system in itself.

The avionics system may serve as an example because its importance has grown enormously and developments take place at a rapid pace. For some types of aircraft about half the design effort is directed toward avionics. Avionic sub-systems include cockpit controls and displays, autopilot and flight controls, communication, navigation and radar as well as all the highly sophisticated military systems for target recognition and acquisition, weapons delivery and electronic counter measures. The aircraft designer is responsible for integrating these many sub-systems which consist of equipment manufactured by scores of separate avionic companies. The design process begins with understanding and defining mission objectives and environment. It continues with the formative phase of investigating alternative solutions and making decisions

iteratively by means of synthesis, analysis, and evaluation. Each system consists of circuits, parallel or in series, with many discrete components. For each of these components the probability of failure can be established by tests; corresponding values for the system can be computed and the overall probability of failure for the system is a clear design criterion. Yet the simple logic of this approach is marred by the tens of thousands of active elements contained in an electronic system and by the large number of parameters which have to be optimized -- e.g. functional capability, maintenance hours per flight hour, cost of development and acquisition, time schedule for testing. Such optimization is usually done by trade-offs based on engineering judgment. Closest cooperation with suppliers of components, realistic detail specifications, and acceptance tests under real-life conditions are fields of special importance where many decisions have to be made.

While the avionics system is the realm of specialists in the field of electronics, other systems are designed by engineers who acquire specialized experience mostly on the job. Even if other systems are hardly as complex as an avionics system, there are basic similarities. Need for a functional and logic diagram, component parts furnished by suppliers, redundancies vs. single components, realistic specifications and acceptance tests -- all these are common characteristics of most systems. The designer has to begin from the viewpoint of synthesis to understand and define objectives and environment and to arrive at alternative solutions, then has to analyze the details, and finally has to integrate all aspects of the system. Again the probability of failure can be established for each sub-system and system but many other parameters with respect to function, weight, cost of acquisition and maintenance, or time schedule have to be optimized. Probability of failure is measured in percent, weight in pounds, cost in dollars, time in days, and it is not always easy to establish a common denominator. Cost in dollars is frequently a practical measure, as for instance in a noise abatement program where the cost can be expressed as dollars per decibel. On the other hand, the value of weight-saving which seems to be such a straightforward consideration is not easily assessed in dollars per pound as it varies with different design phases.

For the decision-making process in systems design we see the overriding importance of establishing the probability of failure at an acceptable level. The magnitude of an acceptable level depends on the consequences incurred by failure. For catastrophic consequences of a failure in a fleet of 200 aircraft with an average lifetime of 50,000 flight hours each, the probability of failure should be less than 10^{-7}.

2.2.5 Structures Design

Structural design is concerned with transmitting loads and moments due to flight and ground loads. Rigorous requirements have to be satisfied at minimum weight and it is a narrow path between too heavy and too light. Wing, fuselage, and empennage structures have always formed the framework of aircraft design with a pervasive continuity reaching from the conceptual to the final design phase.

Contrary to systems which can be represented by a functional diagram with discrete components, the typical aircraft structure serves its load-carrying function as an integral unit. For specified loading and environmental conditions the structure has to satisfy exacting requirements regarding strength, rigidity, weight, cost, manufacturing, processing, durability, reliability, maintainability, vulnerability, and survivability. The challenge to the structures designer is to find the proper balance between these often contradictory demands, and an optimal solution, just as in systems design, is found by trade-offs based on engineering judgment. Each of these diverse aspects has become the domain of specialists. Where there used to be the stress engineer we have now specialists for loads, for static strength, for fatigue strength, for fracture mechanics, for flutter and vibrations. Many of the earlier functions of the designer have been taken over by specialists in cost, producibility, reliability, maintainability, etc.

The analytical aspects of structural design lend themselves, of course, to computerization. NASTRAN, as mentioned in Section 2.2.3, is widely used for the analysis of fuselage, wing, and empennage shells. Many other computer routines exist for strength and aeroelasticity calculations. Yet not much effort has been extended toward bringing quantitative and qualitative

considerations on a common denominator and finding an optimal balance for the inputs of various specialists.

However, an important aspect of computer-aided design should be mentioned here. It is the drafting-oriented computerized graphical design for which Lockheed's CADAM (Computer-graphics Augmented Design and Manufacturing) is representative. CADAM is commercially available and offers savings in timespan and man-hours by about 25 to 75% at reduced cost and improved accuracy. It ranges from design concept to manufactured product and can prepare loft lines, dimensioned drawings, perspective drawings and isometric drawings, charts, graphs, and diagrams; can analyze structural section properties and weights; and can provide N/C cutter tapes for the production of machined parts. The many accrued benefits of CADAM include that repetitive details have to be constructed only once and can be positioned and replicated on a drawing as needed at any scale, and that design changes of common components can be incorporated into thousands of drawings "overnight". For the designer at the graphics terminal existing skills are enhanced rather than displaced.

2.2.6 Design Policy Decisions

Decision-making is important on all levels of design. Yet of special importance are the basic policy decisions which are taken on the top level, particularly during the early phases of design. They include establishment of a value system and of priorities; approval of forecasts about future needs and market developments; selection of major subcontractors; provision for modifications to be anticipated from future customers; evaluation of potential problems, particularly in connection with new developments beyond the present state of the art; appraisal of available resources in knowledge, experience, personnel, equipment, and funding.

In spite of an outspoken engineering flavor, these decisions are of the same kind as corresponding decisions in other fields of management and business administration. Uncertainties and risks often play a dominant role and the counsel of the experienced design engineer is indispensable. Yet only the designer who is familiar with decision-making methods in management can expect to take an active part in such decisions.

2.3 Recent Trends

This brief outline of typical aspects of aircraft design indicates more sophistication in the early phases of parametric design than in the later phases of hardware design. Yet in hardware design a new significance was given recently to design-to-cost, reliability, maintainability and related aspects. Each became the field for a group of specialists -- but basically they remain the designer's responsibility. With the second generation of jet transports the airlines realized that the investment in additional design efforts paid off handsomely in a reduction of maintenance work and unscheduled removals. Correspondingly, the military services realized from the experience with overly sophisticated high-performance aircraft that the groundwork required for maintenance and repair reduced the availability of aircraft by a prohibitive percentage.

Reliability may serve as an example for the kind of considerations which are involved. With the rapid expansion of jet transportation in the early 1960s a large pool of practical experience became available. This service experience was utilized systematically by aircraft manufacturers, equipment suppliers, and customer airlines to improve reliability. It is described by Reesing in Ref. 11 and 12 and a brief summary will give an indication of the typical design effort involved in systems reliability. The main criterion, after flight safety, is high dispatch reliability at low maintenance costs. Logic diagrams for the minimum equipment which must be operating for flight safety are used to display the reliability of each item and the corresponding delay probability. Simplicity, redundancy, and fail-safe characteristics have to be designed into a system from the very beginning. Selection and improvement of components involve much personal contact between the designer who has to accomplish the design objective, airline engineers and maintenance personnel who have had experience with the same or similar components, and the equipment supplier who has to guarantee his product. The design effort starts with searching for the best similar equipment already in service, scrutinizing operational experience regarding mean time between failures, mean time between unscheduled removals, major failure modes, and potential improvements. Design coordination meetings have

to be held before the design begins, during the design process, and when the first production hardware becomes available. The input includes contributions from customer and supplier as well as from specialists in strength, processing, cost, reliability, maintenance, etc. The designer prepares a failure modes and effects analysis, considering all interfaces. Probability and statistics play a major role. Computer simulation with operational flight profile, operating time for each piece of equipment, and failure and repair data on the components provide as an output the probability of delay, of air interruptions, and of flight cancellations before the aircraft is ready for its first flight. The supplier guarantees to meet established performance and reliability values and in case they are not achieved he is obligated to extend his best effort to provide corrective action.

The success of such reliability programs can be seen from the dispatch reliability of aircraft as complex as the L-1011 or DC-10 which is about 98%--i.e. only 2% of the flights suffer more than 15 minutes delay due to mechanical causes. This relatively good operational reliability of commercial transport aircraft, however, is in marked contrast to the situation for military combat aircraft. Here the drive for maximum performance took place at the expense of reliability. Components, particularly in electronics, are often close to the frontiers of scientific knowledge and have not yet reached operational maturity. Even if their reliability is satisfactory under certain test conditions, it often deteriorates quickly under rigorous flight conditions. Of greatest importance are testing programs in real-life environment for each new component. Temperature, vibration, shock, acceleration, humidity, altitude, salt water spray are some of the parameters -- not only their level but also the length of time and sometimes even the rate of change.

Only recently the need has been appreciated to couple performance requirements with strict reliability requirements in military procurements. This means, just as it has been established in commercial transport aircraft, that reliability starts at the beginning of design with clear concepts for simplicity, ruggedness, redundancy, fail-safe characteristics, and derating below design limits. It continues with failure modes and effects analysis, design and producibility considerations, and leads up to quality assurance.

The preceding considerations about reliability refer mostly to systems design. In structures design the designer as well as the structures engineer and materials engineer have been plagued over the last couple of decades by fatigue, stress corrosion, hydrogen embrittlement, fracture mechanics and similar problems which had to be attacked on a broad front of scientific efforts with research on a large scale. Continuing research in the fields of materials science and structural analysis can be anticipated as more high-strength metals and filament composites are developed for structures design. Such developments toward more scientific sophistication are one aspect of future trends in engineering.

A very different trend, however, becomes visible in the renewed emphasis on reliability, maintainability, and design-to-cost. Considerations about maintainability are of a similar kind as what has been discussed about reliability -- an inquisitive anticipation of any difficulties which might be encountered during the service life of the aircraft. Considerations about design-to-cost require an awareness of the overall life-cycle cost which includes acquisition, operation, and support costs. Often in the past these considerations have been rendered insignificant in comparison with the importance given to performance and weight requirements. "Affordability" expresses a cost consciousness which can account for each possible improvement in performance, weight, reliability, maintainability, etc. in terms of cost. Among the avoidable but typical cost drivers are budgetary considerations in Congress, poor visibility of operation and support costs, or unnecessarily complex specifications. Frequently much can be saved by limiting specification requirements to the most essential aspects and encouraging the designer or supplier to submit alternate proposals which indicate the cost of improved performance.

Reliability, maintainability, and life-cycle cost have to be designed into an airplane from the very beginning, just as well as performance and weight. This requires an attitude which only now begins to be appreciated in military procurement. The emphasis in these fields is not on research or a scientific breakthrough but on the traditional virtues of the designer which have been neglected lately and which are summed up in the following section on the essence of design.

2.4 Essence of Design

Summarizing the typical aspects of aircraft design, there are three different fields distinguishable -- each quite distinct in itself and all of them closely interconnected. First, the overall configuration of the aircraft has to be established, with much emphasis on the laws of aerodynamics. Second, the structural framework has to be provided, with much emphasis on materials science and structural analysis. Third, the functional systems have to be established to operate the airplane and provide for the payload, with much emphasis on practical engineering. The emphasis is on a different aspect in each one of the three fields. Yet in each of these basic fields of aircraft design the problems have to be approached in the same way which is typical of design: establish the objective and the underlying value system; find alternative solutions; set up a model and examine each possible solution by methods of analysis and synthesis; evaluate and decide.

Beyond the complexities which may be encountered in the approach to a design problem, there are two basic characteristics involved in a good solution. One aspect is the designer's awareness of the immutable relationship between cause and effect -- even if the effect may become noticeable only after many years of service. The other aspect is the designer's awareness that each component has to be integrated into an entity and that analysis and synthesis complement each other. Such attitude and outlook, combined with the typical design approach, form the foundation of design.

Among the many activities which make up the design process probably the most important and the most pervasive in its many aspects is decision-making. All other design activities are either directed toward making a decision or based on a decision which has been made. The designer's characteristic approach, attitude, and outlook culminate in decision-making.

2.5 Organization of Engineering

To appreciate the decision-making process in aircraft design, it will be necessary to lock at an important organizational aspect of engineering. Each company has a somewhat different organizational set-up, determined partly by earlier developments, partly by resources of personnel and know-how,

and partly by business prospects. However, all of them have one feature in common: there is a distinction between design-oriented and technology-oriented engineers.

This distinction began when the complexities of design grew beyond the capacities of a single person. The designer had to consult more and more technology-oriented specialists and the resulting organizational structure can be represented in form of a matrix. Each of the vertical columns indicates a specialized technology, each of the horizontal rows indicates a design project (and a third dimension could show sub-projects). Designers are responsible for the entirety of their designs and they need width of perspective to appreciate all aspects and to communicate with specialists in many fields. Specialists are responsible for that aspect of a project which is affected by their specialty and they need depth of perception to understand all corresponding implications.

The difference in outlook between designer and specialist means that a decision at any element of the matrix must take into account both the requirements of the overall project and the requirements of the special technology which is involved. Designer and specialists are members of the same team and must appreciate the other's problems. The chief of design bears responsibility for the coordination of all design projects, the chief of technology bears responsibility for the up-to-date competence of the specialists.

These two different orientations toward either design or technological specialty play an important role in decision-making. The matrix form of organization is very different from the pyramid-like organization with the chief executive at the top and the working force at the bottom where decisions are passed down from the top. Engineering decisions of consequence are made on every level of engineering but every decision requires a consensus between the viewpoints of design and technology.

3. STATE OF THE ART IN DECISION-MAKING

3.1 Empirical Approach

Design involves a choice among alternatives. Therefore, decision-making has always been an important part of design. Even in ancient times a pyramid, an aqueduct, a bridge, or a Chinese Wall must have been the result of many design decisions. Much more so in medieval times the architecture of a cathedral, where a primitive level of analytical know-how was combined with a supremely developed sense of synthesis.

Decisions are based either on intuition or on analysis. Intuition, of course, reflects previous experience. Such experience is necessarily limited for each individual and in many cases people are tempted to draw conclusions based on an insufficient amount of evidence. Objective reasoning and subjective feeling are often intertwined, but objectivity ends where the ego begins. All of us are fond of believing that we arrive at our decisions by logical processes -- no matter how much intuition is involved. When others arrive at different decisions, it must be obviously due to their faulty reasoning. How can one judge who is right?

In hardware design the experienced designer has arrived empirically at the decision-making process, based on many years of experience. After 10 to 20 years, good designers feel confident about their intuition because their individual experience has grown into an understanding and insight about the nature of design. They have developed a sense of competence and, depending on the development of the individual, this may cover a broad or narrow region.

At a time when engineering education prepared the student for the practical aspects of design and when a designer had an opportunity to work on many types of aircraft, much broad experience could be accumulated. This situation began to change after the mid-1950s. Engineering education was more and more directed toward analytical methods and specialization, and many of the younger generation of designers have had an opportunity to work only on one or two types of aircraft in a decade because new designs were scarce. This prepared the ground for the typical development of the 1960s: design became the product of team work. The typical team consists of the designer and many specialists who have to contribute their skills regarding

strength, manufacturing, materials processing, quality assurance, cost, reliability, maintainability, etc. Design decisions are made by a team of peers, with the designer more or less as the "primus inter pares".

Some general observations can be made regarding these team decisions. On the whole they seem to be working quite well unless there are adversary circumstances. A good team spirit, expressing the "spirit of the company", is typical. Due to the organizational set-up discussed in Section 2.5, each team member takes part in the decision-making process. This provides a pride of participation as well as a sense of responsibility. Besides, basic rules of engineering common sense are usually followed: decisions are made on the lowest level of competence; decisions are based on consensus among competent people, not on majority vote; decisions must not be influenced unduly by personality or authority; decisions are made by those who are most familiar with all aspects of the problem, i.e. the members of the design team. Only if no agreement can be reached, arbitration has to take place on a higher level which tends to result in summary or imperious decisions and is preferably avoided. A systems engineer may have to make the trade-offs across disciplines.

A clear distinction can be made between a team and a committee or board. The team is oriented toward action, the committee or board toward deliberation and reflection. The design is the outcome of teamwork but it is often influenced by the input from a review board which, in case of an important design, meets at least at the start and at the finish of the design, frequently also at intermediate stages of progress.

As mentioned above, the empirical approach to decision-making within the framework of a design team has generally been satisfactory in hardware design. Much diversified experience is represented by the team members, and intuition is coupled with analytical thinking. However, as the complexity of design problems grows -- as it always does -- two basic weaknesses can be seen: the lack of a scale for comparison and the lack of visibility.

The lack of a scale means that there is no measure for the "goodness" of a design. This refers not only to the overall decision but also to the many components of the decision process. There are qualitative as well as

quantitative values and the quantitative values can be in many dimensions. How can they be introduced into the decision-making process?

The lack of visibility for the decision-making process means that many considerations take place inside the mind of an individual and are neither visible nor traceable. They cannot be checked for accuracy or implied assumptions and have to be taken on faith. Even if the individual can explain them in a discussion, some aspects will remain hidden and often the individual's memory of them may fade soon. As a safeguard, important decisions are frequently written up in form of a design memo and a conscientious designer usually keeps a design notebook or journal. Some companies are more systematic than others in encouraging such practice, but invariably the pressure of time and lack of coordination militate against it -- unless there exists a clearly established company policy to write up a design work package for each major sub-project. This has been done by one of the large companies, based on a soul-searching analysis of previous experience. It involves a considerable effort and includes problem definition, criteria, constraints, assumptions, needs analysis, impact statement, and an outline of alternative solutions. Such a step is, of course, far beyond an empirical approach to decision-making and leads us toward the consideration of the analytical approach.

3.2 Analytical Approach

3.2.1 General Considerations

An analytical approach to decision-making makes use of the methods which are employed throughout science. An initial hypothesis is verified by experiments with repeatable results and followed by general conclusions; mathematical techniques are used as an expression of logical thinking; a rational framework and an orderly procedure are developed. As an outcome of such an approach some insight should be provided about questions like: What is a good decision? How can qualitative values be quantified? Where are judgment and experience utilized?

No matter how decisions are made, the first step is to provide a solid foundation for decision-making in form of problem definition and alternative

solutions. A broad understanding of the problem's implications is needed before necessary information can be gathered and a creative and ingenious mind is needed to perceive alternative solutions. Without these even the best decisions are built on quicksand.

An analytical approach to decision-making distinguishes between problems where the design criteria are single-dimensioned or multi-dimensioned and between conditions of certainty or of uncertainty. For a single-dimensioned criterion under conditions of certainty, optimization is conceptually trivial but often very laborious. A case of complex interactions was discussed in Section 2.2.3 where weight was the single-dimensioned criterion and where uncertainties were removed by simplifying assumptions. When there are multiple dimensions for criteria (e.g. speed in m/h, sonic boom in $\#/in^2$, passenger comfort in terms of quality of life), even if they can be treated as certain, conceptual difficulties arise rapidly. Sometimes they can be overcome by expressing all criteria in terms of a common denominator, such as dollars, and treating the system as single-dimensioned.

Sometimes the following procedure is used for multi-dimensioned criteria: To overcome the difficulty with multiple dimensions, all criteria are made non-dimensional, i.e. normalized, by using a normalizing transformation. To overcome the difficulty that each dimension may have a different relative importance, each dimension is assigned a relative weight between 0 and 1.0 so that the sum of all relative weights equals 1.0. For each dimension the normalized value is multiplied by the relative weight of the dimension and these products are added to obtain an aggregate criterion, the criterion function. A detailed step-by-step procedure for its use is given by Ostrofsky in Part III of Ref. 13. The fundamental drawback of this procedure is that the interaction effects of the criteria are neglected. This may be corrected to some extent by using different rules of aggregation for the criterion function but interactions between criteria are not explicitly examined.

A new order of complexity is introduced under conditions of uncertainty. Such conditions are typical of technological, economic, political, and personal decisions. Research, tests, and experience tend to reduce regions of uncertainty but there is no way getting around the basic fact that man

has to live in a world of uncertainties and has to provide for them in the decision-making process. In some cases uncertainties may be disregarded as negligible or secondary. In other cases heuristic approximation techniques may be useful. For the purposes of this report it will be more important to discuss some developments of a basic nature.

For over three centuries, since the time of Pascal and Fermat, mathematicians have used methods of decision-making under simple conditions of risk -- like tossing a coin, throwing dice, or calculating an insurance premium. In recent decades, for solving the complex problems of our technological world, the use of analytical models has become an important part of operations analysis. Combining these two tools -- simple decisions under uncertainty and analytical models for complex problems -- the new field of decision analysis began to take a firmer shape in the late 1960s. The basic implications and the present state of the art in this field are not widely understood yet and we will briefly summarize them as presented by various contributors in References 14, 15, 16, and 17.

3.2.2 Utility, Preferences, and Information

An important step was taken when von Neumann and Morgenstern published their utility theory at the end of World War II (Ref. 18). Starting from some basic assumptions about "rationality", values in any dimension are converted into the basic dimension of utility. This is done by establishing preferences for the possible outcomes resulting from a decision. Bernoulli had pointed out in 1730 already that the quantity of money is not a measure of its true worth because it has a different meaning to the poor and to the rich. Von Neumann and Morgenstern postulated that a rational person can establish for himself quantitative preferences not only for the outcomes of alternative actions, i.e. value preferences, but also of gambles involving these outcomes, i.e. risk preferences. Based on these preferences a utility function is established in a manner that the decision-maker will be acting in accordance with his own preferences if he chooses the alternative with the highest expected utility.

The utility function is based on a consistent description of the decision-maker's preferences and it provides the means to logical deductions. Outcomes can be in any dimension but under practical conditions they are often expressed in terms of dollars. This leads in extreme cases to the distasteful but logical need to put a money value on human life. The value system has to be consistent for any situation which may occur, including replacement costs for human beings. All aspects of a problem, including those of a non-materialistic kind, have to be considered.

Some comments are appropriate in connection with the concept of the decision-maker's preferences. Obviously these preferences have to be stated explicitly but often they are well hidden in the regions of the unconscious. Neither value preferences nor risk preferences for an individual are established offhandedly. Some introspection is required and practical guidelines and interview techniques have been developed to provide consistency when qualitative values are quantified. When the decision-maker's preferences are known, any competent analyst can establish the utility function and optimize it. No further attention from the decision-maker is required. On the other hand, for an important project the decision-maker is usually not a single person but a group of people, possibly with a strong input from public opinion. In this case the preferences regarding the outcome of alternatives and the attitude toward risk are established by a team effort and again the rest is routine work for an analyst.

Preferences refer not only to values and risk. There are also time preferences with respect to events taking place now or later. In this field the concept of net present value can be used as an indicator. On a more earthy level influences of impatience and greed may be noticeable. Such considerations indicate the wide range of individual preferences entering into a value system--attitudes about time and risk as well as assessments of technological performance, environmental influences, and human ethics. All have to be quantified for the evaluation process.

Decision-making applies the evaluation process to available information. Two aspects of information can be considered: deterministic and probabilistic. The deterministic phase is concerned with the relationships among variables.

An analytical model can be set up to show these interactions and the results are generally obtained in form of a computer program. Sensitivity analyses to show the influence of various parameters are usually included. Parametric sizing as discussed in Section 2.2.1 is a typical example of the deterministic phase (if uncertainties are neglected). Examination of the analytical model can indicate the existence of uncertainties.

The probabilistic phase is concerned with uncertainties. Uncertainty can be expressed in terms of probability as a number between 0 and 1. Impossible corresponds to 0, certain corresponds to 1.0, and the various shades of maybe correspond to the intermediate range. For a set of collectively exhaustive and mutually exclusive elements the sum of the probabilities must add to 1.0.

An objective probability can be based on statistics and experimentation under substantially similar conditions. For many applications of decision-making this is not very helpful. Often an event will occur only once and tests to provide the amount of data necessary to assign an objective probability may be out of the question. This leads to a subjective probability which expresses the state of knowledge about an event. After all, if we would know exactly how a coin is held and tossed and what wind shear will act on it, we could calculate head or tails with certainty by the laws of mechanics. Without getting into philosophical disputes, we may generally consider subjective probability as an application of logic independent of statistical or experimental data. To put it quite explicitly: subjective probabilities are assigned as a measure of our state of knowledge about a phenomenon, not of the phenomenon itself.

To arrive at uncertainty estimates, there is no need for a decision-maker but there is much need for the advice of knowledgeable people with applicable experience. Special interview techniques have been developed to eliminate personal bias as much as possible and to provide a well-considered estimate. This estimate is clearly visible and can be modified if additional evidence makes it advisable. A formal method for revising probability assessments on the basis of new information is available in Bayes' Theorem. The state of knowledge seldom remains constant and uncertainties can often be reduced in due course of time.

Probabilities are generally given not as a discrete value but as a probability distribution which may be in form of a bell-shaped curve. When probability distributions are assigned to variables of the analytical model, the outcome will also be in form of a probability distribution. Typical examples of uncertainty and corresponding probability distribution may occur in the field of parametric sizing when the propulsion system is still under development and its performance data are not yet established. In the field of hardware design probability distributions are encountered almost everywhere. What used to be a deterministic field with well-established margins of safety, admitted the first doubts when margins of safety were recognized as factors of ignorance, and slowly developed into a probabilistic field with probability of failure as a major concept.

A different aspect of the quest for additional information is the need to establish how valuable it is. The value of new information is compared to the cost of acquiring this information. This allows conclusions regarding the direction of new research efforts.

Summarizing the basic aspects of decision analysis which might be of significance to aircraft design: Complex problems can be decomposed methodically into actions and outcomes, giving due consideration to uncertainties and preferences. There are methods for subjective and objective probability assessment and for subjective utility assessment.

3.2.3 Overall Perspective

What is a good decision? Decision analysis indicates clearly that even the best decision cannot guarantee a good outcome when uncertainties are involved. Yet a good decision is the best protection against a bad outcome. A good decision incorporates three major steps: setting up a decision model, establishing preferences, and assessing uncertainties. Having accomplished these three steps means that the essence of a problem is understood. And understanding a problem implies the logical decision.

How can qualitative values be quantified? Decision analysis provides a clear separation between preferences and uncertainties. Preferences are established as the decision-maker's value system. Uncertainties are interpreted

as a part of information indicating the present state of knowledge and are treated in accordance with mathematical laws of probability. For these two different fields the same kind of consistent techniques has been developed for quantification of qualitative judgment.

Judgment and experience, which play such an important but vague role in the empirical approach to decision-making, are just as important for the analytical approach. However, decision analysis applies judgment and experience to well-defined sub-problems which are clearly within the capabilities of the human mind. When it comes to decisions about the more complex problems of our technological world, the unaided human mind is overtaxed. It has to be aided by the computer with its capacity to solve complex problems by established algorithms. Decision analysis attempts to give to man what is man's, namely the basic assignment of preferences and assessment of uncertainties, and to give to the machine what is the machine's, namely the meticulous attention to details, implications, and consequences.

Decision analysis is still young of age and is directed mostly toward business administration and management. In many corporations the decision analyst has become the close associate of the executive. It belongs to the responsibilities of the decision analyst to help to clarify what is taking place in the mind of the decision maker. The essence of decision analysis is to make each part of the decision-making process clearly visible and open to inquiry and examination.

4. SOME PRACTICAL CONSIDERATIONS

4.1 Anticipating Future Developments

We may start out with some considerations about the future. It seems to be a reasonable assumption to anticipate some further lean years ahead for the aircraft industry, followed in perhaps 5 or 10 years by an outspoken demand for a new generation of aircraft which will incorporate recent advances in materials, structures, control systems, and aerodynamics. New developments involve decisions between alternatives. Many of these decisions, particularly about the application of new materials, have to be faced on the level of hardware design. This is exactly the field where the lack of a systematic approach to decision-making has become noticeable in recent years, mostly in the design of new military aircraft when the proper balance between weight, cost, reliability, and maintainability had to be found. In many cases decisions in hardware design have to be made in the face of multi-dimensional criteria and at present the designer is poorly prepared to do this systematically.

An additional consideration can be based on data given by Culotta in Ref. 3. When the precipitous slump occurred in the aerospace industry at the beginning of the 1970s, most of the reduction in engineering manpower took place among younger engineers. Only a negligible amount of hiring has taken place in engineering since then. As a result, the age profile of engineers in the aerospace industry now shows a median age in the mid-forties. This means that in the 1980s there will be comparatively few engineers available with experience in the aircraft industry who are in the most productive age group of about 30 to 40 years and who are much needed for new designs. By far the majority of engineers will be past the prime age for creative and innovative ideas.

In design this general situation has been aggravated because for over two decades engineering education has been tilted toward science. As a consequence, design has held little attraction for promising young engineers. Their scientific knowledge was more appreciated in research and analysis and they shied away from the slow process of accumulating experience in design.

Each of these trends accentuates a situation which has been recognized and clearly expressed by the aircraft industry for some time. There will be a great demand for experienced designers in the foreseeable future but no practical steps have been suggested yet to provide for this predictable need. This is a long-range problem for which no quick solution can be expected.

4.2 Design and Decision-making

In Section 3.2 it was shown that an important concept of decision analysis is the assignment of the decision-maker's preferences and the assessment of uncertainties for each component of a design. A complex design is broken up into discrete elements which can be judged individually by the designer. Subsequent aggregations can be executed by the computer. Each step in the decision process is visible and traceable and forms part of a logical system. This is an outlook which is new but should have a familiar ring to engineers.

It might be helpful to draw an analogy with the concept of systems engineering which spread rapidly in the mid-1950s. When specialization began to play an increasingly important role in engineering, the complex work of the specialists had to be coordinated and integrated into the overall system. This was particularly true in the space program. The systems engineer became a new kind of integration specialist with a background in operations analysis, logic, and mathematics.

To give a trivial example: For a component in a ballistic missile the requirements specified a lifetime corresponding to the flight duration of 30 minutes under severe flight conditions. The component passed its proof test under simulated flight conditions, was then installed in the missile but failed during flight. A second component was built, tested, installed, and failed again during flight. It took a systems engineer to point out that the time required for testing had to be added to the flight time in the design specifications.

As trivial as this example is, it is somewhat typical for the application of basic common sense which is easily overlooked when everyone has a specialized outlook. The designer took the specifications as the gospel truth and the writer of the specifications did not have enough practical experience to add the time for testing to the flight time. While it is the task of the specialist to solve a clearly defined problem, the designer must feel responsible for all aspects of the design -- from the problem definition to the integration into an overall system and maintainability in future service -- and must always be on the lookout for any potential troubles. In this sense the designer should be considered to be the system engineer of a design, whether it is the design of a small detail or of a whole airplane.

Many engineers have an aversion against the term "systems engineering" because it often implies an emphasis on abstract mathematical analysis instead of engineering experience. When the term is interpreted as design synthesis, a design attitude which is aware of all aspects of a design problem, no engineers object. They will point out that they have done this intuitively all the time.

A similar situation seems to exist with respect to decision analysis. Many engineers like to point out that this is not much different from what a good engineer does intuitively anyhow. Yet the crucial point is that human intuition becomes quite unreliable under complex conditions. Decision analysis relies on consistent logic, orderliness, and visibility. An intuitive approach is always on feeble grounds when it has to contend with an analytical method or when plain credibility has to be established.*

*One is reminded of the story about Euler at the sophisticated court of St. Petersburg over two centuries ago. He was questioned relentlessly by the enlightened philosophers how he could consolidate his religious faith with his mathematical genius. Finally he replied with some mathematical formulas beyond their comprehension and concluded: ergo God exists. Fortunately, however, the decision analyst has to refrain from such tricks because it would be too easy to call the bluff.

Both systems engineering and decision-making are based on an abstract logic. Systems engineering has assumed a particularly visible role in the hardware design of Air Force projects. It is used mostly as a check-up or bookkeeping function regarding safety, survivability, and logistics independent of the design hierarchy. Within the design hierarchy the designer represents the integrated viewpoint of systems engineering which coordinates the work of specialists. The relationship between designer and specialists affects decision-making. This relationship is somewhat different from one company to another, often even in various groups within a company. Notwithstanding some notable exceptions, in general the designer can be considered to be in a weaker position than the specialist. This observation cannot be proven quantitatively but it is rooted in basic aspects of engineering education.

4.3 Design and Engineering Education

Engineering education has always been built on a solid scientific-deterministic foundation. Since the mid-1950s, however, some aspects which are typical of design have been widely neglected in favor of science-oriented subjects. Among them are those which are particularly important for decision-making: development of a sense for synthesis and an awareness of uncertainties. This is the underlying cause for the present neglect in the field of decision-making. Engineers are well equipped to think analytically with regard to a clearly defined deterministic problem but they are in general poorly prepared for the solution of complex ill-defined problems under uncertainties. Yet these are the kind of problems which become increasingly important in a technological world.

Some steps have been taken to ameliorate the situation. Introductory design courses for freshmen and interdisciplinary design courses for seniors have been introduced at several universities. New developments are taking place in experiential learning. The Engineers Council for Professional Development attempts to emphasize the importance of design in the accreditation of engineering curricula. The magnitude of the task can be appreciated when one realizes that it takes years to develop an analytic-deterministic mind in the undergraduate student. It is a comparable undertaking to

develop in the student a sense for synthesis and an awareness of uncertainties.

At our universities an analytic-deterministic mind is developed in students of science and engineering by science-oriented faculties. A sense of synthesis and an awareness of uncertainties are developed in students of operations research by operations-oriented faculties. These are two different worlds. They speak somewhat different languages and there is not much communication between them.

Decision-making in engineering design is a field where these two worlds have to meet and where communication and mutual understanding have to take place. The situation is aggravated by the lack of experience which science-oriented and operations-oriented faculty members have in aircraft design and by their lack of contact with engineers in industry who are building up this kind of experience. There exists a triangle of non-communication between engineering faculties, operations research faculties, and design engineers in industry. To reverse this situation by establishing a triangle of communication is not easy. Aerospace faculties are retrenching in view of a greatly reduced number of students and often this means just more specialization. Operations research faculties are too remote from engineering problems. And engineers in industry are under pressure of time with everyday problems.

Faculties, of course, educate students in their own image. Since most faculties are research-minded in line with the academic trends of more than two decades, students cannot be expected to be educated for design. They are well educated for analysis and research but the demand in these fields has dwindled. The majority of engineering positions in industry are more design-oriented than research-oriented. Industry needs engineers who combine an analytical mind with a sense of synthesis -- a rare breed in our universities.

Since so many universities have fallen short in this respect, the question is whether engineering technology curricula or continuing education can provide a remedy. Engineering technology programs are still in an early stage of development and it would be premature to draw conclusions, as their

first graduates came out during the years when the aerospace industry could absorb very few of them. Continuing education draws many of its teachers from capable engineers in industry who can put their practical experience to good use for the benefit of the students. Unfortunately there is a great lack of design-oriented text material -- a deficiency which is also strongly felt among university faculties.

4.4 General Implications

The deliberate process of making decisions is one of the most basic characteristics of the human mind. It is the subject of much research in the fields of neurology, brain physiology, psychology, and their interacting border regions. Engineering concepts are used frequently in life sciences. By the same token, the engineer concerned with decision-making might well be in touch with corresponding concepts in adjacent fields.

For instance, in brain physiology efforts are made to interpret the brain in analogy both with the digital computer and with holography -- two concepts familiar to the engineer. In psychology there is a concept which may be of special interest: When the mind is confronted with a new situation and decisions have to be made, this can result either in motivation and action or, if the complexities are overwhelming, in emotions and frustrations. This is in line with the basic principles of decision analysis.

It is important to see intuitive and analytical approach to decision-making in the proper perspective. Every-day life is full of decisions which are made intuitively without any hesitation. No need exists for doing it differently. On the other hand, there are important decisions in business life which justify the expenditure of much time and money to consider all aspects and consequences of a problem. Between these two extremes there is the broad spectrum of problems where the method of approach might be somewhere between purely intuitive and purely analytical. Expense of the analysis and magnitude of the problem must be kept in proportion.

It seems surprising that engineers have been largely unaware of the developments in decision analysis. Engineers think analytically and decision analysis should be close to their hearts. It is an anomaly that engineers

depend on an intuitive approach when it comes to the crucial point of decision-making. This basic situation is somewhat hidden because for engineers intuition is interspersed with analytical thinking. In many cases this may lead to the *illusion that the demands of rationality have been satisfied.* It is a dangerous illusion as long as the overall logic is not clearly established and made visible.

Beyond these considerations there is a very fundamental aspect of decision analysis which has been expressed by Edwards in Ref. 19 in the form: "Decision-making is too simple for executives to waste time on it". Executives merely have to make sure that they are in agreement with the clearly visible input for preferences and uncertainties. The remainder is routine for the decision analyst. This is the situation which has to be envisioned as a consequence of the logical analytical approach discussed in Section 3.2.

5. PROBLEM AREAS AND BASIC NEEDS

We may now try to rearrange the preceding discussion to identify principal problem areas and to recognize some basic needs.

5.1 Decision-making -- General Problem

There is a deep-rooted incongruity in the approach to decision-making in aircraft design. On one hand, many important decisions in hardware design are made intuitively. This is usually done by a team of competent and experienced engineers, after due discussion, but nevertheless decisions are taken without making the line of reasoning clearly visible and traceable or measuring the merits of alternative solutions. On the other hand, during the early parametric phases of design when the aircraft geometry is determined and the mission analysis is performed, decisions are based on an analytical approach. This is done by a team of engineers who combine design experience with an understanding of operations analysis. Even if simplifying assumptions are used, they are shown clearly and decisions are based on a visible and traceable logic and corresponding optimization.

This incongruity is generally not yet considered to be an urgent problem. In hardware design any difficulties caused by diverse qualitative considerations are solved "from experience" because the rigorous methods of decision analysis applied to complex problems are time-consuming and outside the confines of traditional engineering. Besides, the practical outlook and the "can-do" attitude of most designers have always been inclined toward an empirical approach, using analytical methods only as need arises for specific problems. Therefore, an empirical approach to decision-making in hardware design has always been considered to be satisfactory.

The present investigation starts from the premise that this situation is not necessarily irrevocable. It was pointed out that great strides have been taken in decision analysis in recent years and that it is anomalous for engineers with their analytically inclined minds to be unaware of these developments. It was also pointed out that in the foreseeable future there can be expected to be a great demand for capable designers who have to make decisions in the face of multi-dimensional criteria.

As an example for multi-dimensioned criteria we have seen the present concern about designing not only to minimum weight but also to minimum cost and maximum reliability, maintainability and survivability. Each of them is approached as a single objective because the designer is not prepared to find an optimum balance among them. Quite interestingly it has been only in recent years that these basic aspects of design rose to prominence, although each of them is as old as design itself. Under the pressure of such trends each major aircraft manufacturer put much effort into educating groups of specialists in these fields. The expensive task of writing and keeping-up-to-date manuals and handbooks in these fields was undertaken by each company separately based on its individual experience. Much duplication of effort took place because no centralized effort existed. This was, however, understandable as some companies had accumulated experience which was considered to be proprietary. As an unavoidable by-product of this development, the designer tends to become more alienated when specialists take over.

A similar situation may easily come up with regard to decision-making. This, too, is a subject as old as design itself. It has been much neglected but it may assume prominence at any time. No proprietary considerations exist in this field. Would it not stand to reason to prepare the ground for a common approach -- if a meaningful step could be taken as a low-keyed effort?

These considerations about a general approach to decision-making in aircraft design focus attention on the following basic need: A feasibility study has to establish whether and to what extent available methods of decision analysis are applicable to hardware design. Since no proprietary considerations are involved, the waste of unnecessary duplication can be avoided and a moderate-scale "seed" program may be initiated by a government agency or a private foundation. The method of approach would be that the project investigates several typical applications of decision-making to hardware design and pursues each example with due regard for the viewpoints of design experience as well as decision analysis. Each example could be investigated in cooperation with one of the major aircraft manufacturers.

Regarding practical aspects: The cooperation of the aircraft industry is necessary and may consist of making a few experienced engineers available for several hours of consultation, advice, and discussion. This cooperation

should be expected in view of the clear benefits to industry derived from such a project. To avoid difficulties with incidental proprietary information, the project would have to be conducted by a contractor outside the aircraft industry. Good results at minimum expense have been obtained in the past under similar conditions when graduate students used such projects for thesis work under the guidance of a faculty member. Close cooperation between engineering faculties, operations research faculties, and design engineers in industry would be necessary.

5.2 Decision-making -- Specific Aspects

No matter what the conclusions will be from the feasibility study proposed in Section 5.1, there remains the general problem area of considering uncertainties in design. The root of the problem is, of course, that probabilistic aspects are generally neglected in engineering education. This is a problem which exists independent of decision-making but is much aggravated when the need for decision-making arises.

To understand uncertainties requires a background in probability and statistics. These subjects have been developed on an abstract mathematical level. Their application to the abstract level of parametric design causes no basic difficulties. Their application to practical levels of business administration and management mushroomed when textbooks were provided with real-life examples from the world of business and economics. Unfortunately, there is a total lack of such real-life examples from the field of engineering. This means that even if engineering students take a course in probability and statistics, the subject does not easily come to life as long as they cannot apply it readily in their own field of interest.

Probabilities of failure have become important in subjects like systems design , strength of materials, reliability, and quality assurance. There are many other aspects of uncertainty, e.g. attitude of the boss, preferences of the customer, politics, public opinion, etc. They have to be brought into the open to bring them into proper balance with other information. Wilmotte discusses in Ref. 20 the think-positive syndrome which inevitably tends to obscure uncertainties until they become clearly visible as deficiencies. Vandivier in Ref. 21 shows an example how this can reach crisis proportions.

These considerations focus attention on the basic need to provide illustrative real-life examples from aircraft design in the fields of uncertainty, probability, statistics, optimization, and design synthesis. Such practice-oriented text material is most essential to make designers fully aware of the implications of uncertainty. One practical approach to obtain such material may be in connection with the feasibility study proposed in Section 5.1. Another practical approach may be in connection with the case studies proposed in Section 5.4 or otherwise just collecting applicable examples from aircraft design. Only a comparatively small effort is needed to bear much fruit.

5.3 Aircraft Design - Basic Problem

There is a wide-spread lack of recognition and appreciation for the significance of design, for its functions and responsibilities. Until the 1950s the designer's position was held in high regard. Then specialists in scientific technology began to take over more and more of the designer's responsibilities. Striving for maximum performance in a special field, each specialist made full use of scientific expertise to arrive at conclusions. Broader overall responsibilities, however, compelled the designer to base conclusions on practical experience and judgment. This divergence of outlook had the consequence that the prestige of design declined at a time when science rose in public esteem.

Such unbalance between design and technologies is contrary to the spirit of engineering organization as shown in Section 2.5. Design is directed toward integration and the designer is responsible for accomplishing the design objective by optimal means. Technologies are directed toward specialization and technological specialists are responsible for making full use of available knowledge in specialized fields. Design and technology complement each other and are organized for cooperation and coordination. They are equally important. Both design outlook and technology outlook are solidly rooted in the same deterministic logic of engineering sciences but design needs an additional root in the probabilistic logic of operations research.

The reason for the ascent of specialists during the past two decades can be seen clearly in the rapid expansion of scientific borders.

Science-oriented specialists were needed and the universities provided them. More recently, with increasing emphasis on the "-ilities", practice-oriented specialists are becoming more frequent (while theoreticians of operations research also take a strong interest in these fields). In either case, more of the designer's functions are taken over by specialists.

Many of the developments of the recent past and the near future are not problems of technology. They are basically problems of design and illustrate how wide the designer's range of responsibility reaches. The designer must take responsibility for optimization of the overall system. This includes science-oriented performance as well as practice-oriented "-ilities" -- sophisticated techniques as well as old-fashioned design virtues. Such a wide range of concern requires the insight and competence of an exceptional person. It means that an important part of the designer's responsibility is to communicate with the specialists and to understand the essence of their problems -- leaving it to the specialists to find the solutions in special fields.

Provision for an adequate supply of well-educated, talented, and experienced designers is an obvious necessity. Unfortunately, the harsh reality is that most of the experienced old-time designers are getting close to retirement age; that it has been very hard to attract promising engineers to design; and that, as shown by Culotta in Ref. 3, the age profile of engineering departments in the aerospace industry after the great slump of the early 1970s predicts an outspoken shortage of engineers in their most productive years at a time when many will probably be needed. For design the prospects are particularly bleak because it has been handicapped for a long time by science-oriented engineering education (see Section 4.3). As the present old-time designers with their solid experience fade away, a new generation of designers seems to be poorly prepared to present the case for synthesis when technological specialists propose analytical solutions which may be well-documented but one-sided.

This focuses attention on the basic question: will specialization take over or will design reassert itself to demand its rightful place? This question has been obvious and urgent at least since the early 1970s but no substantial action has been taken and the drift toward specialization has

continued. It is a foregone conclusion that specialization will win by default unless decisive steps are taken toward design.

The need for a strong position of design as a balance to the present dominance of technologies has been implicit throughout this report. Industry is strongly motivated in this direction but no solution is in sight unless enough capable designers are available. As a very fundamental step a general awareness has to be developed for the need of a design outlook as the necessary complement to the technological outlook. This design outlook is imaginative and inquisitive; it is based on both deterministic and probabilistic thinking; and it is satisfied only when all possible interactions and combinations as they may occur under real-life conditions have been fully considered.

The need for a design outlook is recognized, to somewhat varying degrees, throughout the aircraft industry. It is not appreciated at most universities. As a consequence, the most promising graduates from our best universities have been hardly aware of it. They have shied away from design because they did not recognize the challenge of it. Much "missionary work" still has to be done to develop a general perception of this new outlook. Computer-aided design, system optimization, and decision-making under uncertainties are the new challenges which have to be met but which have a basic appeal to analysis-minded engineers. They have formed the main content of this report and they require familiarity with sophisticated techniques. However, there is also the very basic significance of traditional design responsibilities and they will be discussed in the following section.

5.4 Aircraft Design -- Specific Aspects

Experience has always been a most essential part of design. After 10 to 20 years of experience the designer has encountered and digested many kinds of design problems, has recognized that not even the most methodical approach provides sufficient guidance through the existing diversity of problems, and has developed a design attitude which is a necessary complement to any design methodology. Such a design attitude is always on the lookout for real-life complexities, for uncertainties and hidden parameters, for the continuity from design to operation of a product, for the relationship between cause and effect, and for interactions between parts, between people, and between man and machine.

Experience cannot be learned. What can be learned, however, is a readiness to learn from the experience of others, to recognize the root of a problem, to understand and evaluate contributing factors, and to transfer judiciously the lessons learned from one problem to another. The designer traditionally has been left to his own devices, slowly accumulating this kind of experience over decades. This is as inefficient as it can be and industry simply cannot afford to continue along these lines.

Much valuable work has been done in the form of Engineering Case Studies -- in analogy to the cases in medicine and law which have served for a long time as precedents for solving similar but different problems in the practice of the profession. A large library of Engineering Case Studies was developed during the past decade at Stanford University, supported by NSF, and is now administered by the American Society for Engineering Education. The cases are based on real-life experiences which are significant as examples of complex engineering problems, with a detailed description of all complexities and the considerations which finally led to the solution. Most cases were chosen for their general applicability and only very few are taken from aircraft design. Yet an excellent collection of cases for aircraft design exists in aircraft accident investigations which provide first-rate material to develop an awareness of the importance of smallest details. It would take only a small effort to make this gold mine of experience readily available to every student of design. An understandable reticence of the industry in this field should be overcome by the realization that most accident investigations indicate the high level of competence and conscientiousness incorporated in the design procedure and the role played by a combination of circumstances and, besides, that these investigations are a matter of public record and that there is nobody in a position to throw a first stone.

These considerations about case studies in design as well as the previous considerations about examples for intuitive and analytical approach to decision-making and about examples for uncertainty, probability, and statistics all point in the same direction: there is a great need for real-life examples from aircraft design. Availability of such examples can shorten the time to accumulate design experience by a very appreciable factor. Implicit in these considerations is the combination of analytical aspects emphasized

for decision-making, system optimization, and computer-aided design and of design experience emphasized in connection with the "-ilities".

5.5 Education for Design Engineers

There remains a very pertinent question: How can engineers be prepared for the tasks of design and decision-making? An answer will have to start with the somewhat resigned but realistic appraisal that hardly any early help can be expected from universities because of the science-orientation of present faculties. The best prospects are provided by continuing education in close cooperation with industry. Within the present framework of continuing education, courses can be offered in subjects like design, decision-making, probability and statistics. The teachers would be drawn largely from industry. Basic text material is available in all these subjects but it is not aero-oriented. With the aid of well prepared real-life examples from aircraft design, as proposed on the preceding pages, these courses can be made meaningful and stimulating to engineers in the aircraft industry. If such courses coincide with a clear appreciation for the significant functions and responsibilities of design, they can provide the essential step toward a well-balanced relationship between project-oriented designers and technology-oriented specialists. It can be hoped that a re-orientation toward design will take place at the universities in due course of time.

Such an approach to education for design appears reasonable and practical. It is based on the premises that a moderate-scale but effective support can be provided by a government agency or private foundation for the development of essential practice-oriented text material; that ample talent is available in industry to teach such courses when this text material is available; that a realistic effort must be focused primarily on engineers in industry and only secondarily on engineering students at universities; and finally that the "missionary work" mentioned at the end of Section 5.3 is an integral part of the effort.

6. CONCLUSIONS

Assessment of Present Situation:

a. Looking at aircraft design from an overall perspective, two major trends can be recognized: First, during the past few years a new emphasis has been given to the basic but long-neglected virtues of design to cost, reliability, and maintainability. Second, in the near future a high degree of sophistication will be required of the designer as computer-aided design will be generally introduced and a new emphasis on system optimization and decision-making is likely to develop. A new generation of designers will have to master the full spectrum from old-fashioned design virtues to sophisticated techniques.

b. From the viewpoint of decision-making, the state of the art can be summed up as follows: On the level of parametric sizing, much analytical work is done attempting to achieve optimization and design synthesis. On the hardware level of design, however, most major decisions are made empirically by the design team -- using an undefined mixture of intuition and analysis, usually without a visible and traceable logic for the decision-making process.

c. The approach to design and decision-making consists of a basic sequence: establish the objective and the underlying value system; find alternative solutions; set up a model and examine any feasible solution by methods of analysis and synthesis; evaluate and decide. The experienced designer tries to do this intuitively. Yet an analytical approach is based on recognizing the simple biological fact that the unaided human mind is quite inapt for solving complex problems. Complexities rise rapidly when uncertainties are involved -- as they usually are under real-life conditions.

d. Decision-making under complex conditions has been developed in operations research. The implications are simple and far-reaching. Three basic aspects are involved:

   - A problem is understood only when it can be expressed clearly. For technological problems this means an analytical model.

- Human judgment depends on a subjective value system. The decision-maker's preferences have to be stated explicitly. They are open to discussion and modification.
- Human knowledge is subject to uncertainties due to incomplete information. Uncertainties have to be assessed and revised as additional information becomes available.

The engineer has always been inclined to employ the rational first aspect. The two subsequent aspects are concerned with the intangibles of real life conditions. They are characterized by human follies, limited knowledge, and by an uncertain future. Any design has to stand up under such real-life conditions but at present the typical designer is not fully aware of their importance and is poorly prepared to face them.

Problem Identification:

e. On the level of hardware design, decision-making and optimization will require a new approach emphasizing visibility and an awareness of uncertainties and of preferences of the decision-maker.

f. The fundamental problem is that decision-making is a part of design and that design has been neglected in engineering education for over two decades.

Proposed Course of Action:

g. With respect to decision-making, there is a basic need to clarify whether and to what extent basic aspects of decision analysis can be applied to decision-making in aircraft design. This is discussed in Section 5.1 and leads to the first recommendation in Section 7.

h. Since decision-making is a part of design, a basic concern must be directed toward the neglect of design in engineering education. As discussed in Sections 5.2 and 5.4, an essential step can be taken by developing practice-oriented text material and offering design-oriented courses to engineers in industry within the existing framework of continuing education. This leads to the second recommendation in Section 7.

i. During the next decade it can be expected that recent advances in research will pose formidable challenges in design, e.g. new materials, fly-by-wire, control-configured vehicles, etc. However, the general trend for engineers has been away from design for a long time. Besides, the age profile of aerospace engineers gives a clear warning that most of them will be beyond the prime age for creative and innovative ideas when the new challenges arise. Unless decisive steps are taken soon, a lack of capable designers may easily jeopardize the leading position of the U.S. aircraft industry.

j. There is no lack of talent in specialized fields. More significant is the question whether a trend away from over-specilization can be encouraged. A wide-spread nostalgia and longing may be sensed in connection with design-oriented terms like "old-time designer", "Dassault approach", or "skunk works". It appears that many a capable engineer could be attracted to design if the transition would be furthered and stimulated by design-oriented courses in continuing education (see item "h") and by a general awareness of the genuine need and promising future for a design outlook as the necessary complement to the technological outlook, as discussed in Sections 5.3 and 5.5.

k. To summarize this design outlook concisely:

- The designer has the overall responsibility for a design project while each specialist has responsibility for a special aspect of it;
- A hierarchical system of well-defined responsibilities reaches from the designer of the total system to the designer of a small component;
- At any level of the design hierarchy the designer's approach to a design problem (as summarized in item "c") and to decision-making (as summarized in item "d") is basically the same;
- With increasing complexities a new emphasis has to be given to preferences and uncertainties involved in design and to system optimization;

- In hardware design, systems engineers who are familiar with preferences and uncertainties usually are in an ambiguous position because physical engineering aspects are all-pervasive and the typical systems engineer is not familiar with them;
- Therefore, the designer has to become familiar with the principles of decision-making to solve routine problems regarding preferences and uncertainties. The operations analyst will be needed for the more complex problems.
- Finally, as a most important point: With all the additional emphasis on analytical aspects, the basic asset of a good designer still remains a creative, imaginative, and inquisitive spirit.

l. Such a design outlook can be effective only when it is practiced by highly capable designers. They need a solid background in engineering science to communicate with technological specialists and to understand their problems; a good feeling for design practice to appreciate interactions and real-life complexities; and an understanding of the basic principals of operations analysis to integrate diverse aspects as well as to assess uncertainties.

m. This puts extraordinarily high demands on a new generation of designers. Under present conditions these demands are met by a few rare individuals who combine background, experience, talent, and initiative and who are quickly promoted into management. To develop this capability in a great number of designers calls for educational vision coupled with a high regard for practical experience. The old-time designer who slowly accumulated decades of personal experience can be succeeded by a new type of designer who builds on decades of stored general engineering experience -- if this experience is made readily available in form of practice-oriented text material.

n. Design as the planning stage of engineering can also be considered in a broader context. In a compact and characteristic form it encapsules the same basic problems which haunt our technological world in many other fields, e.g. urban development, transportation, economics,

politics, armament policy. There are capable specialists everywhere but there is a great lack of people who have both depth of perception and width of perspective. If this problem can be solved in aircraft design, much may be learned for other fields.

o. As a final conclusion, an important point can be appreciated. Any good decision has to be based on a consensus of competent people. This can be reached only when a value system has been clearly established and uncertainties have been assessed. Such a consensus must express a full understanding of the problem. In this sense the philosopher and the decision analyst agree: any problem holds its own solution which becomes visible and obvious when the problem is fully understood.

7. RECOMMENDATIONS

First, to clarify the potential role of decision-making in aircraft design, it is recommended that a government agency or private foundation in cooperation with the aircraft industry sponsors a moderate-scale project in line with the discussion of Section 5.1.

Second, to take an essential step toward design education, it is recommended that a government agency or private foundation in cooperation with the aircraft industry takes the initiative to develop practice-oriented text material for design courses. As discussed in Sections 5.2 and 5.4, this can be done on a moderate scale and might be combined with the preceding recommendation.

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